ACQUISITION AND REDUCTION OF LARGE VOLUMES OF FLUCTUATING DATA

By

Luke A. Schutzenhofer and Paul W. Howard

SUMMARY

The definition of the spatial and spectral decomposition of unsteady physical phenomena is commanding a new role in space vehicle development. For example, unsteady pressure fluctuations on the surface of a launch vehicle induce vehicle buffeting, local shell and panel vibrations, and internal noise. Presently, a description of these unsteady phenomena is derived from model testing where sophisticated data acquisition and reduction techniques are required. This paper describes an experimental program in which large volumes of random (in space and time) data were generated and provides some of the details of the overall requirements, the data acquisition system, amplitude and phase calibration techniques, static and dynamic operating characteristics of the data acquisition system, component qualification testing, model vibration testing, and the data reduction technique.

LIST OF SYMBOLS

Symbol	Definition
A	amplitude of a sinusoidal wave
B	amplitude of a sinusoidal wave
f	variable frequency
f_o	fixed frequency
G(f)	cross-spectral density or power spectral density function defined for non-negative frequencies
H(f)	frequency response function
i	$\sqrt{-1}$
j	index
k	index
K	constant value of a white noise spectrum
M_∞	free stream Mach number
P	pressure
Rn/ft	Reynolds number per foot
S	cross-spectral density for positive and negative frequencies
t	time variable
T	averaging time
X	time-dependent variable (input)
Y	time-dependent variable (output)
z_k	variable space coordinate vector in index notation
z_j	variable space coordinate vector in index notation
z'_k	particular (fixed) space coordinate vector in index notation
z'_j	particular (fixed) space coordinate vector in index notation
α	angle of attack
δ	dirac function
χ	roll angle
τ	delayed time
ϕ	phase angle

Subscripts

1 and 2 indices	denotes different systems, phase angles, or frequencies

∞ infinity

Superscripts

$*$ denotes complex conjugate.

INTRODUCTION

The spatial and temporal definition of design environments pertaining to unsteady physical phenomena is commanding a new and important role in space vehicle development. This is particularly true in the cases of rocket exhaust noise, ground winds, and inflight fluctuating pressure fields. The acute impact of possible adverse effects of these physical phenomena demands that a meaningful (however complex) engineering description of them be provided at the earliest possible time during the vehicle's research, development, and operational phase. Realistic vehicle design criteria cannot be formulated until a meaningful engineering description of the space-time fluctuating environment is achieved.

In each of these cases, best engineering estimates for vehicle design are derived primarily from model testing, and in each case, astronomically large volumes of space-and-time-dependent data are generated. To provide the minimum (even this is a tremendous volume) amount of data needed for a foundation upon which realistic design criteria are to be based, the data must be computer-analyzed, scaled, and organized into meaningful engineering terms. The engineering terms for all of these design environments are statistical quantities, i.e., root-mean-square values, power-spectral density, and cross-spectral density functions, because the time-dependent physical processes creating the environments are random processes. Previously, data acquisition and reduction systems were not capable of measuring the most important parameter, the cross spectral density, because they could not retain phase with sufficient accuracy. Therefore, earlier wind tunnel programs were concentrated on obtaining overall mean-square values and power-spectral densities for engineering application. Realistic environmental design criteria cannot be derived without knowing the cross-power spectral density.

To gain an appreciation of the large volume of data and the experimental detail required to successfully estimate design environments caused by time-dependent random physical processes, this paper describes an experimental program and its associated data acquisition and reduction requirements to determine the inflight fluctuating pressure (inflight acoustics) design environment for the Saturn V.

ENGINEERING APPLICATION OF RANDOM PRESSURE DATA

To determine the inflight fluctuating pressure field design environment for the Saturn V vehicle, it was necessary to fabricate a four percent model of the vehicle and conduct a series of tests in the largest wind tunnels available: the AEDC 4.9-m (16-ft.) transonic and supersonic tunnels. Once the unsteady surface pressures are measured and properly recorded, it is necessary to reduce them to statistical quantities including overall root-mean-square values, power-spectral densities, and the "pressure cross-spectral density function" for engineering application. Then we can (1) delineate buffet loads for estimating vehicle body bending response computations, (2) determine local fluctuating pressure loads for input to local panel and shell mode structural response calculations, and (3) define the inflight external acoustic environment to determine vehicle internal noise levels. These applications are necessary to assess vehicle integrity, determine realistic margins of safety, and insure mission success.

REQUIREMENTS

Before a complex test program can be conducted successfully to measure unsteady surface pressure fluctuations, guidelines for the following six items must be specified: (a) instrumentation and aerodynamic requirements, (b) qualification tests for the data acquisition systems to establish their performance characteristics in the field environment, (c) a meaningful amplitude and phase calibration scheme for use at the field test site, (d) a plan to define the static and dynamic characteristics of the data acquisition and reduction system, (e) a data acquisition system to measure the dynamic vibration response of the model-sting configuration and other components, and (f) a data reduction procedure that is technically adequate and economically practical.

The objective of this paper, to reveal the complexities associated with the data acquisition and reduction, can now be achieved by considering in detail each of these requirements.

INSTRUMENTATION AND AERODYNAMIC REQUIREMENTS

To insure the correct measurement of the primary fluctuating physical process, that is, the unsteady surface pressure fluctuation on the four percent Saturn V model, instrumentation specifications called for flush-mounted microphone measurements of noise levels, internal microphones to assess the effect of model vibration on the unsteady data, accelerometers to measure model-sting accelerations, static pressure transducers to measure surface static pressures, pressure rakes to measure total pressures, and internal thermocouples to measure internal temperature. The additional measurements, i. e., internal microphones, accelerometers, thermocouples, etc., were required for interpreting and establishing the utility of the unsteady pressure data. Table I shows the measurement plan by number and type.

TABLE I. NUMBER AND TYPE OF MEASUREMENT

Number	Type of Measurement
140	Surface dynamic pressure
5	Internal dynamic pressure
10	Model-sting acceleration
320	Surface static pressure
5	Pressure rake, 9 to 15 probes
10	Internal thermocouple

Since the buffet loads, local shell and panel unsteady loads, and external sources of internal noise require the determination of the "pressure cross-spectral density," a constraint that is not found in conventional aerodynamic engineering tests existed in this test. This constraint is phase retention. For example, given a surface being acted upon by an unsteady pressure field which has statistical characteristics that are independent of time translations, the pressure cross-spectral density is defined as

$$S(z_k, z_j, f) = \int_{-\infty}^{\infty} \left[\lim_{T\to\infty} \frac{1}{2T} \int_{-T}^{T} P(z_k, t)\, P(z_j, t+\tau) \right] e^{-i2\pi f\tau} d\tau. \tag{1}$$

If the pressure fluctuations at z_k and z_j are given, respectively, as

$$P(z_k, t) = A\delta(z_k - z'_k)\sin(2\pi f_o t + \phi_1)$$
$$P(z_j, t) = B\delta(z_j - z'_j)\sin(2\pi f_o t + \phi_2), \tag{2}$$

then, the cross-spectral density of the fluctuating pressure field for positive frequencies is

$$G(z_k, z_j, f) = \frac{AB}{2}\delta(z_k - z'_k)\,\delta(z_j - z'_j)\,\delta(f - f_o) \left\{\cos(\phi_2 - \phi_1) + i\sin(\phi_2 - \phi_1)\right\} . \tag{3}$$
$$0 \leq f < \infty, \text{ otherwise zero}$$

From equation (3), it can be seen that phase retention is required in cross-spectral density estimates. As a result of this requirement, a data acquisition and reduction system was required that would resolve phase within $\pm$ 5 degrees at 20 kHz. This system was also required to be capable of measuring mean-square amplitudes in the range of 135 to 173 dB within 10 percent. It was necessary to design, build, and test a totally new (multiplexing) data acquistion system for this purpose, since conventional systems could not even come close to those stringent requirements. This represented a major advance in acquiring phase-related information in large quantities over a relatively large frequency range, i.e., 20 Hz to 20 kHz.

It is worth noting that the pressure cross-spectral density is a cross product and a function of frequency. If all necessary combinations of cross products were computed at one test condition for 100 possible pressure transducers for 27 one-third octave bands, the resulting number of data points would be equivalent to the number of data points generated from 1500 static tests. Thus, it is easy to understand how large volumes of data are generated from one model test, considering that the above crude analogy was for one test condition and that many test conditions must be covered.

To meet these requirements, the general specifications and the multiplex concept were initiated and resulted in the data acquisition system shown in Figure 1. This system was designed and built by and under the supervision of the Experimental Aerophysics Branch of the Aerophysics Division, Aero-Astrodynamics Laboratory. A thorough laboratory test of the equipment was also conducted by this organization.

The microphones, Kistler model 601L, have their first resonant frequency at 130 kHz and an output of 6.89×10^{-9} C/N/m^2.

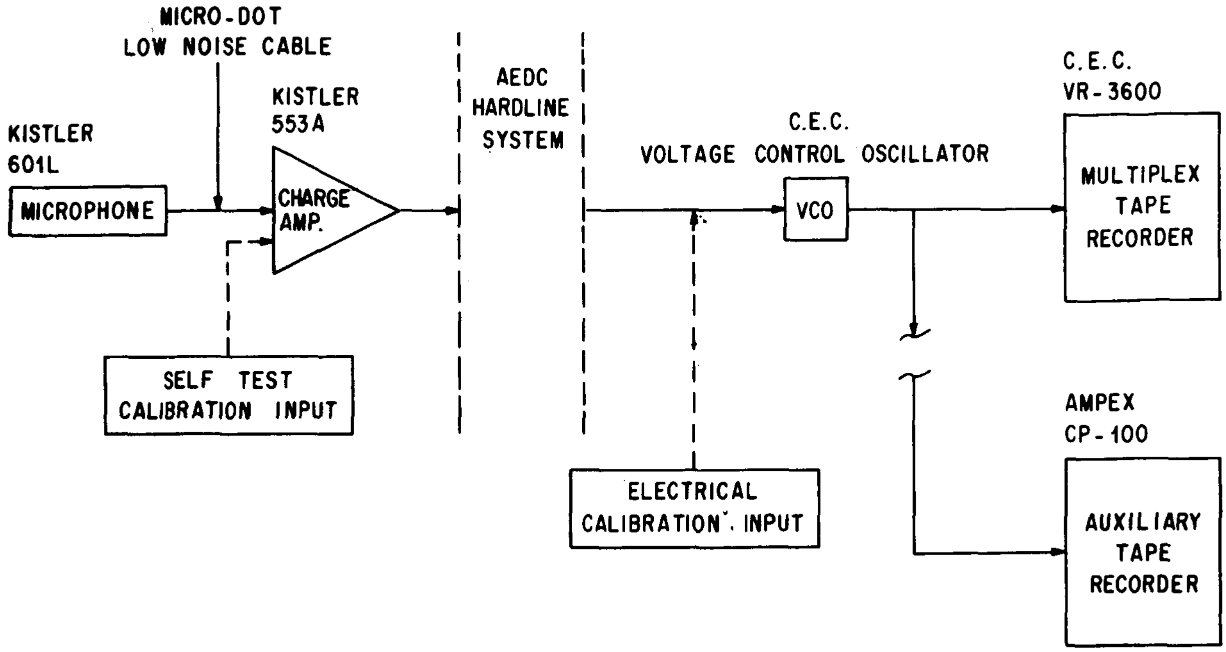

FIGURE 1. FLUCTUATING PRESSURE DATA ACQUISITION SYSTEM

The amplifiers, modified Kistler model 553A, are a constant-phase type and have a flat frequency response range from 20 Hz to 80 kHz.

The main recorder, a C.E.C. VR-3600, can record frequencies of 1.5 MHz on each of 14 tape channels. On each of the fourteen tape channels, nine multiplex signals were recorded, each with a 20 Hz to 20 kHz flat frequency response. This particular arrangement, with a modulation index 2, limited the upper usable data bandwidth to 20 kHz. A larger number of measurements with a lower upper-frequency limit is also possible. Some data were recorded on an Ampex CP-100; these data were not multiplex.

A typical microphone installation is shown on Figure 2. Also shown in this figure are some pressure rakes, protuberances, and static pressure orifices.

To measure the static and total pressures, pressure scanners made by Scanivalve of San Diego, California, were used in conjunction with a Statham model PM 131TC pressure transducer.

The model-sting vibrations were measured with C.E.C. model 4-203-0001 accelerometers along with Endero model 4402 signal conditioners.

The model internal temperature was obtained with a thermocouple.

This test program was conducted in two phases at the Arnold Engineering Development Center's Propulsion 4.9-m (16-ft.) transonic and supersonic wind tunnels. Phase I testing was transonic and was conducted in tunnel 16-T; phase II testing was supersonic and was conducted in tunnel 16-S.

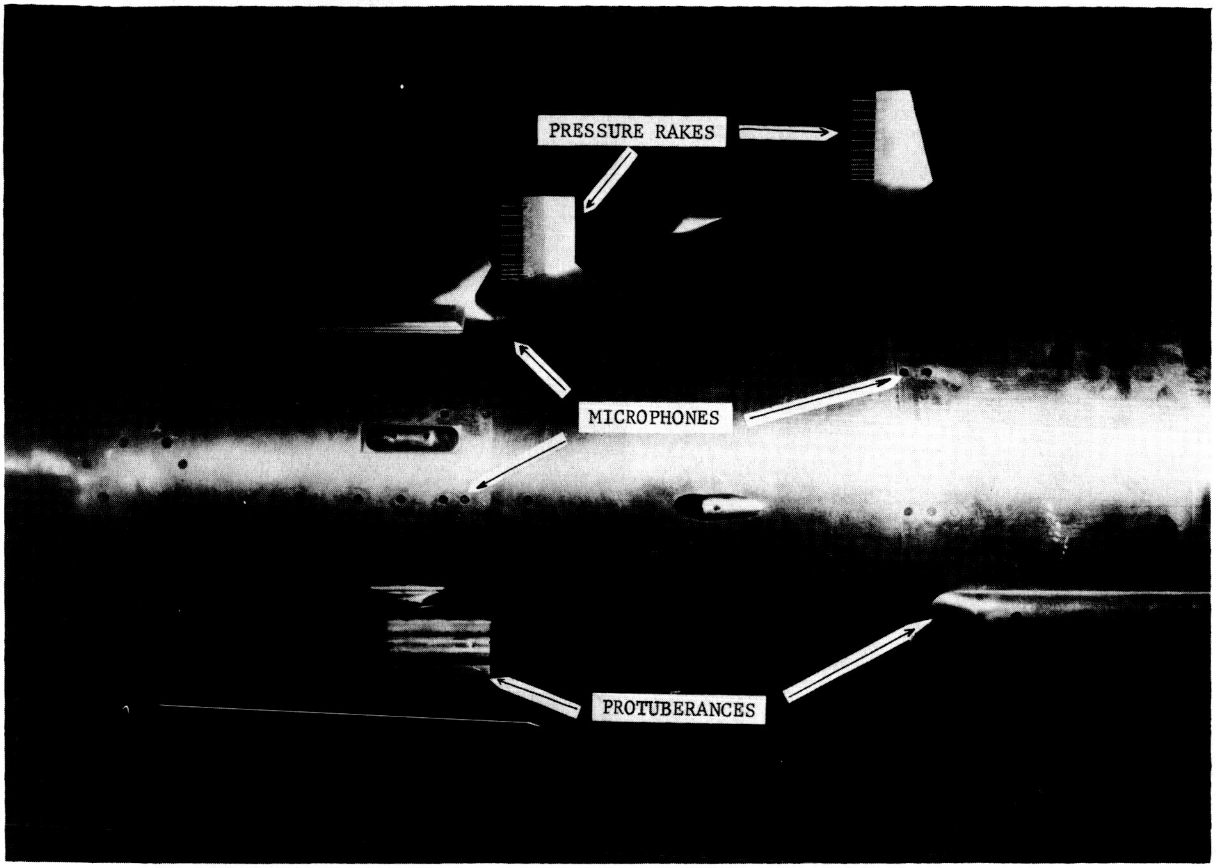

FIGURE 2. TRANSDUCERS, RAKES AND STATIC PRESSURE ORIFICES

During phase I testing, the range of parameters was as follows:

$0.6 \leq M_\infty \leq 1.4$, $-10° \leq \alpha \leq 10°$, $0 \leq \chi \leq 60°$, and

$4.2 \leq Rn/ft \times 10^{-6} \leq 4.9$.

A Mach number sweep (at a slow rate) was executed because the locations of some violent unsteady phenomena are extremely Mach number sensitive, and since transducer locations are fixed, then discrete incremental Mach number testing may or may not produce the maximum environment at the transducer.

During phase II testing, the range of parameters was as follows:

$1.6 \leq M_\infty \leq 3.0$, $-4 \leq \alpha \leq 4°$, $0 \leq \chi \leq 60°$, and
$1.0 \leq Rn/ft \times 10^{-6} \leq 2.0$.

In both phases of this test, two model configurations were used. Figure 3 shows configuration I with protuberances, and Figure 4 shows configuration II without protuberances.

QUALIFICATION TESTS FOR THE DATA ACQUISITION SYSTEM

After the data acquisition system was designed and the aerodynamic objectives delineated, qualification tests were conducted to determine if the components of the system exposed to the wind tunnel environment could survive and perform within specifications. The dynamic pressure transducer, amplifiers, and cabling were qualification tested at the facilities of Ling-Temco-Vought, Inc. These systems were subjected to and passed a variety of tests including vibration, high-temperature environments, etc. [1].

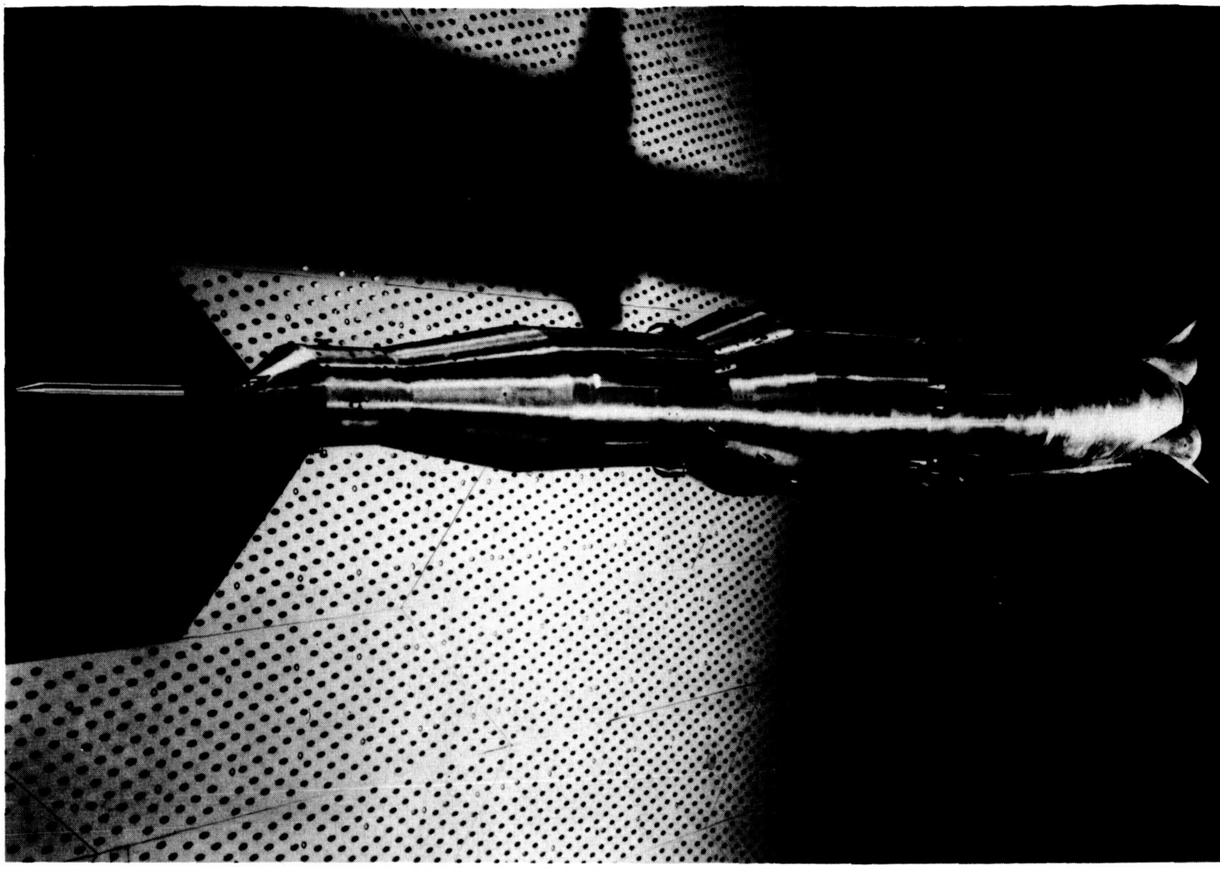

FIGURE 3. CONFIGURATION I

AMPLITUDE AND PHASE CALIBRATION PROCEDURES

To amplitude calibrate the flush-mounted microphones, a Photocon PC-125 acoustical calibrator that had a known output of 160 dB (0.00002 N/m^2 at 1 kHz) was used as a source. This source was applied to the microphone systems to determine their amplitude sensitivity. This procedure was done three times for each transducer for each phase of the testing, and an average amplitude sensitivity was computed from the three results for each test phase. The deviation from the average was small (on the order of 4 percent). As an additional system check, an electrical signal of 1 kHz was input (inserted) at the voltage control oscillator. The system output generated by this inserted electrical signal was recorded on every tape.

Because of the large volume of data to be recorded and the complexities of the data acquisition system, an absolute phase calibration would have been extremely time consuming, if it could be done at all. However, since the primary concern is "cross-spectral" density computations, relative phase is more important than absolute phase. It was assumed that the data acquisition system, the dubbing (copying on other tapes) process, and the data reduction system could be treated as lumped constant-parameter linear systems. With statistically stationary random inputs, the cross-spectral density of the two outputs of any two of the lumped systems in terms of the cross-spectral density of the inputs and the systems frequency response functions can be shown to be

$$G_{y_1y_2}(f) = H_1^*(f)\, H_2(f)\, G_{x_1x_2}(f), \qquad (4)$$

$$0 \le f < \infty\ , \text{ otherwise zero}$$

where $G_{x_1x_2}(f)$ is the cross-spectral density data

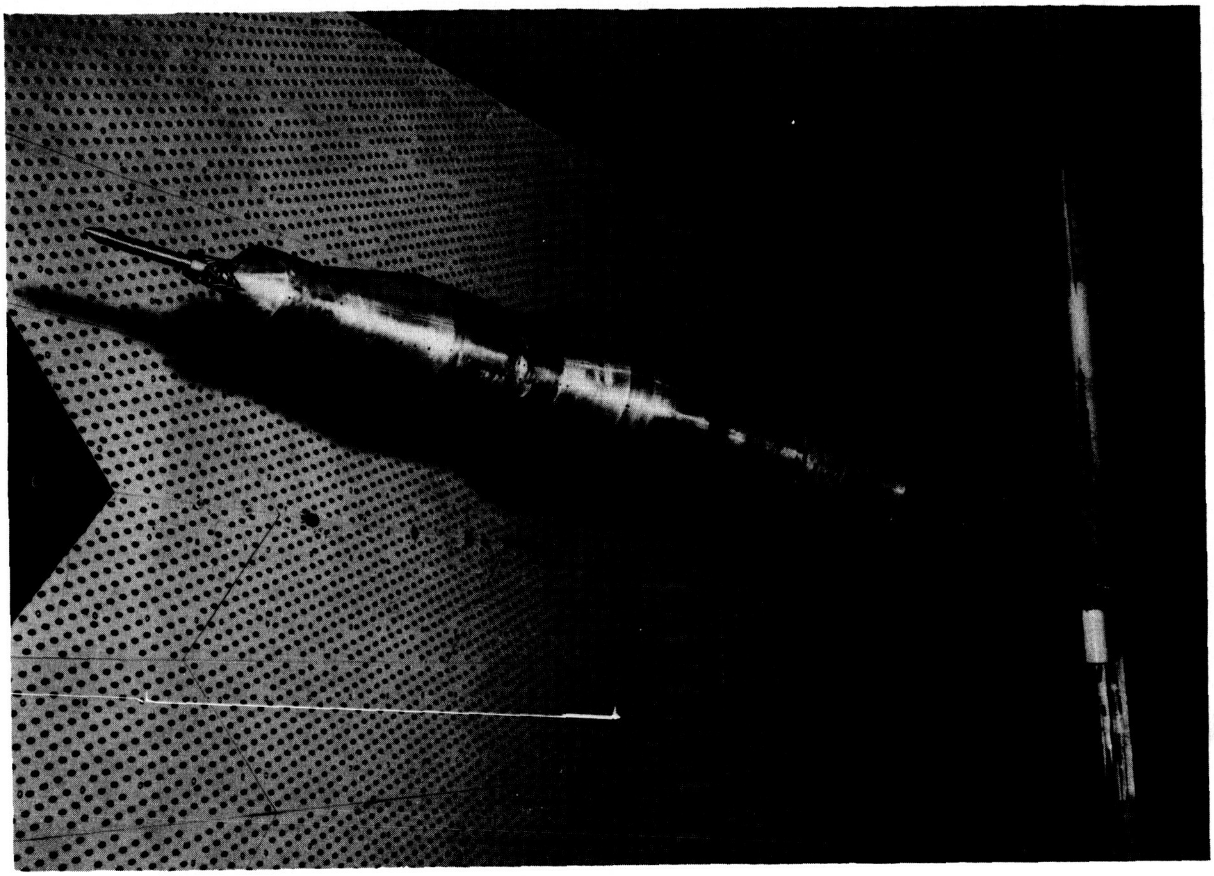

FIGURE 4. CONFIGURATION II

that we are attempting to obtain, and $H_1^*(f)\ H_2(f)$ are the system's lumped constant distortions. Now $H_1^*(f)\ H_2(f)$ is the product of two transfer functions (each characterizing a given system), is independent of the input, and needs to be determined only once. This product then characterizes the two systems, and thus the amplitude and phase distortions will be known between two acquisition-to-reduction channels. It was decided to input a common single-source band-limited white noise at the self-test circuit of all the Kistler charge amplifiers. The cross-spectral density then becomes

$$G_{x_1x_2}(f) = G_{x_1x_1}(f) = K, \qquad f_1 \le f \le f_2 \qquad (5)$$

otherwise zero

where $f_2 - f_1$ determines the limiting bandwidth. Therefore,

$$H_1^*(f)\ H_2(f) = \frac{G_{y_1y_2}}{K}(f). \qquad f_1 \le f \le f_2 \qquad (6)$$

otherwise zero

Consequently, the entire lumped system relative characteristics for the $f_2 - f_1$ frequency bandwidth are determined from the white-noise test. This recorded information is used in the data processing to estimate and correct for phase distortions.

EXPERIMENTAL PROGRAM TO DETERMINE SYSTEM STATIC AND DYNAMIC CHARACTERISTICS

In addition to the field calibration procedures, field instrumentation tests were performed by Measurement Analysis Corporation to determine the data acquisition system's noise floor, frequency response, amplitude linearity, and intermodulation distortion. In other words, experimental test of a complex instrumentation system's total characteristics was conducted at the field site for comparison against conventional laboratory tests to accomplish this task. Detailed analyses are now underway but are not yet completed; however, cursory analyses indicate no major problems.

VIBRATION TEST OF THE INSTALLED FOUR PERCENT SATURN V MODEL TO MEASURE MODEL-STING RESPONSE.

During the week of the Phase I testing, Lockheed Missiles and Space Corporation, Huntsville, Alabama, performed a vibration test on the model-sting configuration with all model data acquisition systems active. Figure 5 shows the vibration test set up. The intention here was to determine (1) model-sting mode shapes and frequency response and (2) the sensitivity of all the model data acquisition systems to a vibration input only.

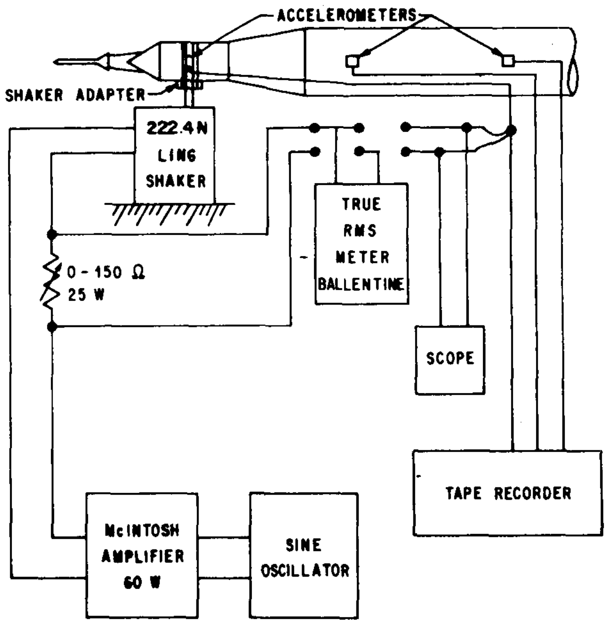

FIGURE 5. VIBRATION TEST OF A FOUR PERCENT SATURN V MODEL

The vibration test was conducted for the first four pitch modes. The fundamental resonant frequency of the system was about 5.76 Hz. Analyses of these data are in progress; however, the large amount of fluctuating pressure data already analyzed does not seem to be seriously affected by model vibrations.

DATA REDUCTION PROCEDURE

The data reduction, i.e., the analyzed cross-spectral density data resulting from the experiment is being performed by Baganoff and Associates. The analyses are being performed in one-third octave bands.

The mean square spectral density in a one-third octave band, using an ideal unit rectangular filter, corresponds to the average over a one-third octave bandwidth of the mean square value per bandwidth. If the cross-spectral density is a monotonically varying function in a bandwidth and if the slopes of the modulus and phase angle are not steep, the one-third octave band value is a good approximation to the point function. For example, calculations [2] using triple-tuned filters indicate that for a worse case, the modulus (amplitude) could be in error at most by 5 percent and the phase could be biased by 5 degrees. In the general applications intended, the bulk of the data are smooth and continuous; therfore, the one-third octave band analysis was used because it is an excellent compromise between application of the data, the time required to reduce the data, and the cost of reduction.

The one-third octave band cross-spectral densities are being obtained by analog techniques. The system being used to analyze the four percent Saturn V model data is shown in Figure 6. The averaging time, or the time required to compute the cross-spectral density for one pair of measurements is approximately $7\frac{1}{2}$ minutes for a 30-second sample.

With averaging times of 30 to 45 seconds, phase-angle deviations of $\pm$ 5 degree peak-to-peak at 20 kHz have been achieved in 92 percent of the white-noise calibration test cases. This phase accuracy of the total system, i.e., data acquisition, dubbing, and reduction chain, at such high frequencies is unprecedented for this type of testing and represents a significant advance over conventional systems. Before this system was developed, it was impossible to produce cross-correlation data for engineering applications by wind tunnel model testing of a given vehicle configuration.

CONCLUSIONS

In the acquisition and reduction of large volumes of fluctuating data pertaining to the four percent Saturn V model experiment, we can make the following conclusions:

1. Mean square amplitudes have been resolved within a 10 percent scatter band.

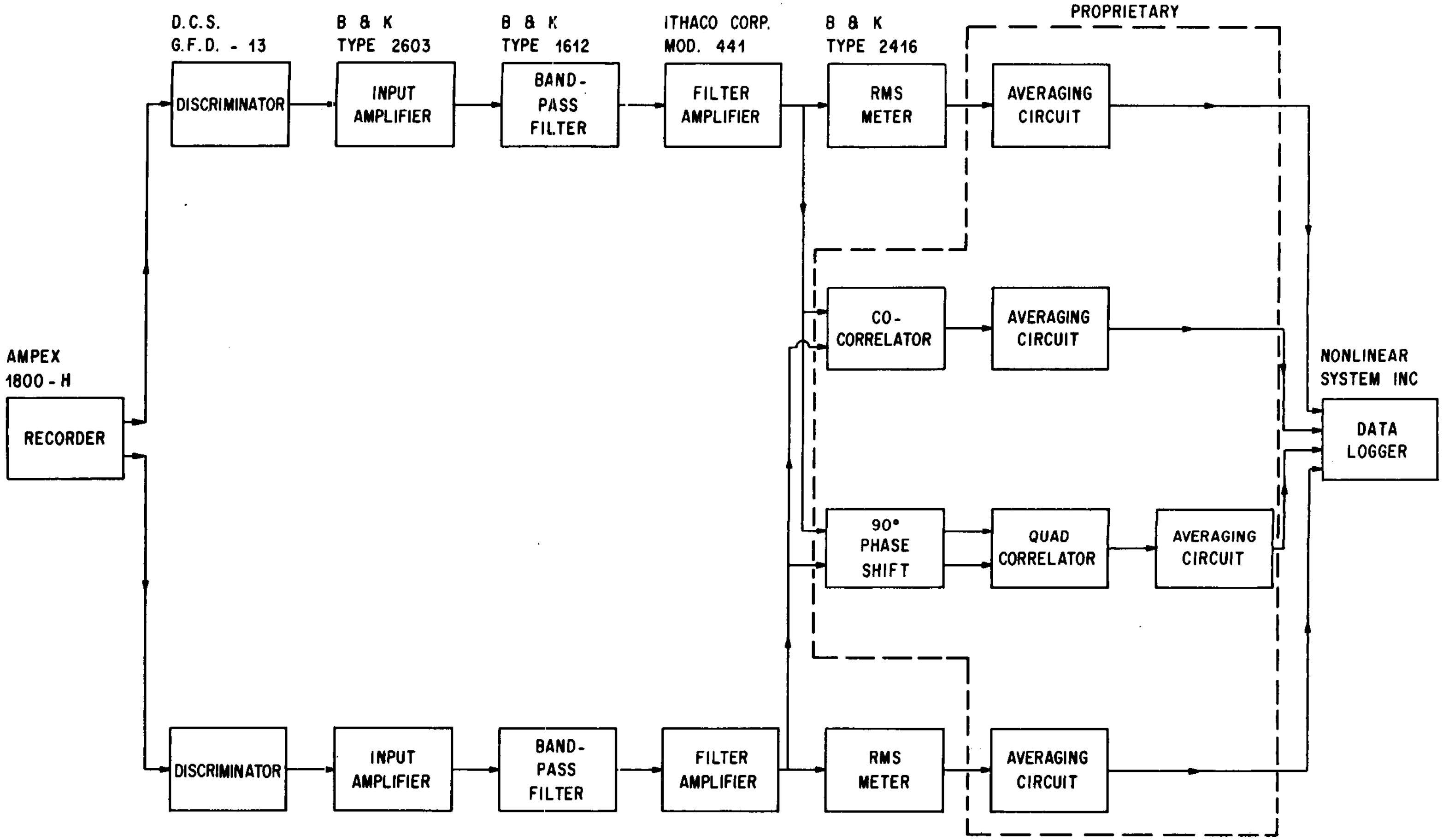

FIGURE 6. DATA REDUCTION SYSTEM

2. The data acquisition system successfully passed all environmental qualification tests.

3. Field instrumentation tests were performed and the results are being analyzed to determine the data acquisition system's static and dynamic characteristics under field conditions as compared to laboratory-controlled conditions.

4. Mode shapes, frequency response, and vibration sensitivity are being determined from model-sting vibration tests.

5. The data acquisition system's vibration sensitivity is being established with the field data acquired from the internal acoustic and vibration measurements.

6. This is the first time that 122 channels of phase-related random data with $\pm$ 5 degrees (at 20 kHz) phase distortions have been recorded successfully. This represents a major advance over the conventional approach to this problem and therefore allows the generation of cross correlation information for engineering purposes for the first time. Before this, such information was so limited that it was used primarily for research purposes only.

7. One-third octave band spectrum analyses are technically adequate and economically practical in these types of large-volume data analyses.

8. Comparisons are being made between the model data and Saturn flight data.

9. This has been the first successful attempt in using band-limited white noise to establish relative phase distortions.

10. This data acquisition system, calibration scheme, and data reduction system combination is unique and represents a significant advance in the state of the art. Additionally, this system is versatile, and its use is not limited to fluctuating pressure tests.

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2. Kelly, R. D.; and Mauner, J. R.: Filter Mismatching Errors in Cross-Spectral Density Analysis. Measurement Analysis Corporation Report MAC 703-06, January 1968.